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RESEARCH ARTICLE

Blockchain technology as an enabler for sustainable business ecosystems: A comprehensive roadmap for socioenvironmental and economic sustainability

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Abstract

Blockchain technology is a core technology expected to play a highly instrumental role in competing with socioenvironmental challenges. The literature hypothesizes various blockchain functions for building a sustainable business ecosystem. This study unifies these diverse perspectives into an interpretive strategy roadmap that provides a holistic overview of how blockchain should be leveraged to deliver sustainability functions optimally. The study first identified the sustainability functions of blockchain through a content-centric literature review. The study applied interpretive structural modeling (ISM) and drew on experts' opinions to model how and in which order blockchain delivers these sustainability functions. The study further drew on the ISM output and interpretive logic-knowledge base to develop the promised roadmap. Results revealed that blockchain promotes a decentralized decision system that facilitates automation and real-time information sharing (RIS) across supply chains. Blockchain introduces traceability and transparency into supply chain operations. These conditions offer monitoring of business operations and the development of trust across value-chain stakeholders. These driver functions lead to value chain optimization and circularity integration into business and supply chain operations. When these necessary functional conditions are met, businesses can further draw on blockchain to promote economic and environmental aspects of sustainability through more complex functions enabling resource efficiency, cost reduction, pollution prevention, and higher profit margins. The order in which businesses can leverage these functions would define blockchain sustainability performance. Each function is uniquely valuable to sustainability, and none of them can be overlooked.

KEYWORDS

blockchain, decentralization, digitalization, supply chain, sustainable business, traceability

1 | INTRODUCTION

Given the level of integration among economies and nations, regional conflicts like the Russia-Ukraine war have multitudinous far-reaching effects. This is why we can see the impact of this conflict entrenching from social, political, and economic to environmental. From the environment perspective, the conflict has not only contributed to environmental degradation directly but also indirectly by hampering the global environmental governance process. There is the silver line in the cloud in the form of European countries speeding up efforts to build long-term clean energy sources to reduce their dependencies on Russian gas. The pursuit of green energy could be significantly paced up by capitalizing the digital technologies. Adopting such technologies can help reduce energy consumption at one end and can help build clean energy resources at the other end. In contrast to conventional wisdom, blockchain technologies have the potential to augment this pace of adoption. Experts believe that blockchain can be leveraged to address many enduring sustainability challenges if managed correctly and with the right mindset (Friedman & Ormiston, 2022; Khan, Razzaq, et al., 2021; Leng et al., 2020). Blockchain is a distributed ledger that uses cryptography to link blocks of data. It is decentralized because no single group of users has complete control over data, and instead, all parties involved collectively retain control of data (Di Vaio & Varriale, 2020). It is also immutable because data, when filled in blocks chronologically and chained to other consecutive blocks, are irreversible and tamperproof (Zutshi et al., 2021). Blockchain operates on the peer-to-peer (P2P) networking of data and eliminates the trusted third parties' role in ensuring the security and authenticity of information or transactions (Howson, 2020; Li et al., 2018). Overall, blockchain is characterized by its safety, transparency, traceability, security, and decentralization characteristics, which are believed to offer practical implications for advancing sustainable development (Parmentola et al., 2022).

The literature provides miscellaneous insights into how blockchain can build a more sustainable world (Sislian & Jaegler, 2022). Indeed, blockchain fulfills this role through its various sustainability functions, some of which are prominently acknowledged, while some are less known (Khanfar et al., 2021). The decentralization feature of blockchain may address the socioeconomic inequality issues by empowering the stakeholder-centered distribution of wealth (Alves et al., 2022). Indeed, blockchain can promote the concept of participation-based value creation where, instead of a privileged group of shareholders controlling the value creation network, the entire network of stakeholders can benefit from the growth of the value network (Corrêa Tavares et al., 2021). Alternatively, blockchain traceability and transparency features can be an essential enabler of environmental accountability within industrial supply chains (Agrawal et al., 2021; Centobelli et al., 2022). These features allow supply partners and stakeholders to have a clear view of the socio-environmental performance of raw materials, operations, and products (Venkatesh et al., 2020). Therefore, the traceability and transparency features of this technology can address some of the long-lasting sustainability concerns of supply chains, such as child labor, harmful emissions, or compliance issues (Guo et al., 2020).

Literature also offers early evidence on how blockchain might improve operational efficiencies (Khanfar et al., 2021). Businesses can leverage blockchain to optimize the distribution of materials and products and achieve efficiency in inventory management and order fulfillment (Ho et al., 2021). More importantly, blockchain can complement other Industry 4.0 technologies such as the Internet of Things (IoT) and machine learning to enable cognitive manufacturing systems where optimization of manufacturing processes can improve sustainable manufacturing performance in terms of material efficiency, waste reduction, and emission prevention (Leng et al., 2020). Alternatively, and viewed from the macro-societal perspective, blockchain can play a critical role in advancing sustainable development goals (Parmentola et al., 2022). For example, de Villiers et al. (2021) theoretically described how businesses might promote the United Nations' sustainable development goals by innovating their business model functions based on the complementarity of blockchain and IoT and their unique features such as real-time connectivity or data transparency. Parmentola et al. (2022) took a more holistic view and theoretically argued that blockchain can promote sustainable development goals by empowering supply chain sustainability, circular economy, and greening the energy sector.

Despite the hype surrounding the sustainability implications of blockchain, little to no studies have identified the micro-mechanism (functions) through which the sustainability implications of blockchain can be developed and implemented. More importantly, the literature tends to micro-analyze the individual sustainability functions of blockchain theoretically and in isolation. This knowledge gap poses a challenge for individual firms or chains of supply partners that need to strategize their blockchain-based business digitalization agenda to strike a balance between competitiveness and various sustainability priorities. Blockchain contributes to sustainability through a complex system of functions. We believe there is no exclusivity among the blockchain sustainability functions. Instead, these functions are sequentially interrelated, and complex precedence relationships might exist among them. Consistently, the present study aims to model the micro-interaction of blockchain sustainability functions and identify possible synergies and dependencies among them. To this purpose, the study conducts a comprehensive content-centric review of the literature and identifies various sustainability functions of blockchain. The study further draws on the Interpretive Structural Modeling (ISM) technique and experts' opinions on micro and macro blockchain-sustainability interactions and develops the strategy roadmap explaining how blockchain should be leveraged to enable sustainability. This model is expected to provide sustainability actors, supply chain partners in particular, with a holistic view of how blockchain can lead to a more sustainable value-creation ecosystem.

2 | BLOCKCHAIN AND SUSTAINABILITY

The sustainability concept builds upon a simple principle: humans and the natural environment should coexist in productive harmony to fulfill present and future generations' economic and social needs (Ghobakhloo et al., 2022). Consistently, it covers three distinct areas of economic, environmental, and social sustainability. Sustainability has long been the center of attention for various scientific disciplines. The scientific community has shown much interest in explaining how disruptive technological innovations can contribute to sustainability, and blockchain has been no exception. Although this game-changing technology is very new and its application for business transformation is still largely unknown, recent literature offers valuable insights into blockchain opportunities for sustainability.

Previous studies have addressed blockchain's sustainability contributions from diverse perspectives. A significant portion of existing research explains how blockchain can lead to sustainable supply chain management (Paul et al., 2021). For example, Saberi et al. (2019) explained how the blockchain smart contracting feature could address sustainability concerns. They also described barriers to adopting blockchain technology within the sustainable supply chain management context. Esmaeilian et al. (2020) explored how the transparency and smart contracting features of blockchain can promote sustainable supply chains in the Industry 4.0 context. Esmaeilian et al. (2020) further revealed that blockchain interacts with other Industry 4.0 technologies like IoT to improve sustainability performance metrics such as product lifecycle visibility. Previous studies also offer important insights into the industry-specific implications of blockchain for supply chain sustainability. Within the food industry context, examples include exploring blockchain roles in introducing sustainability into the halal food supply chain (Ali et al., 2021), agri-food supply chain (Rana et al., 2021), and global food supply chains (Friedman & Ormiston, 2022). Guo et al. (2020) viewed the supply chain sustainability implications of this technology from a different perspective and observed that blockchain could streamline the fashion supply chain's sustainable efforts by facilitating information disclosure over environmentally-friendly operations such as using green materials. Other contributions from this stream of research involve exploring blockchain implications for green supply chain governance (Kleinknecht, 2021), sustainability-driven supply chain mapping (Kusi-Sarpong et al., 2022), and supply chain green performance management (Paul et al., 2021).

Another stream of research addresses the implications of blockchain for sustainable manufacturing and production. For instance, Leng et al. (2020) proposed the blockchain-enabled sustainable manufacturing architecture in which they explained how this technology could empower sustainability by increasing the efficiency of equipment management, production scheduling, and resource management within manufacturing systems. More importantly, Leng et al. (2020) proposed capitalizing on blockchain for developing more environmentally friendly business models such as open production or cloud manufacturing. Alternatively, Li et al. (2021) explained how blockchain and IoT could be integrated to develop an intelligent prefabricated construction system that serves sustainability by promoting green innovation and material efficiency. Other significant contributions to this research stream include identifying blockchain features and their impact on improving the sustainable performance of manufacturers (Khanfar et al., 2021) or defining blockchain applications for developing sustainable production capability evaluation (Li et al., 2020).

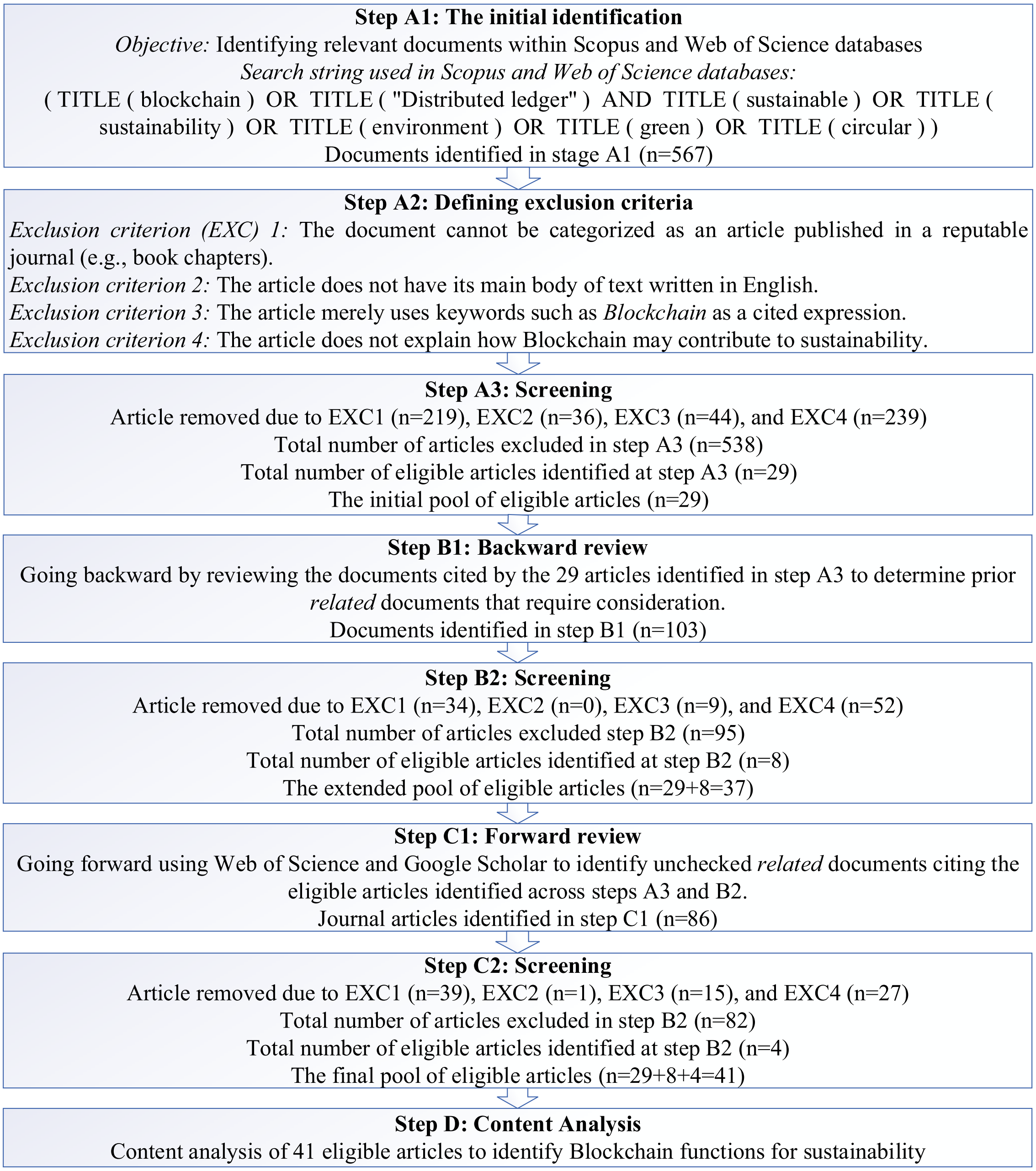
Some recent studies hold meso and macro perspectives to explain how blockchain might contribute to sustainability by changing the structure of the economy and society (e.g., Ajwani-Ramchandani et al., 2021; Upadhyay et al., 2021; Venkatesh et al., 2020). Blockchain implications for the circular economy have received considerable attention within this research stream. Researchers believe that blockchain's unique features, including transparency, smart contract, trust, and traceability, can advance the circular economy by streamlining reverse supply chain processes such as remanufacturing, recycling, or prolonging (Centobelli et al., 2022; Nandi et al., 2021). Although the early understanding regarding the enabling role of blockchain for the circular economy was mainly theoretical (Kouhizadeh et al., 2020), more recent case studies offer valuable practical insights into the application of this technology for developing more circular business models (Gong et al., 2022).

Despite the relative novelty of this research discipline, the literature provides important insights into the micro-mechanisms through which blockchain can enable various aspects of sustainability at the micro and macro analysis levels. Nevertheless, the literature falls short in merging the existing perspectives to holistically explain whether various sustainability functions of blockchain are mutually exclusive or they can be developed under a shared business ecosystem to offer superadditive sustainability value.

3 | SUSTAINABILITY FUNCTIONS OF BLOCKCHAIN

The study followed Webster and Watson's (2002) and Watson and Webster's (2020) literature review guideline and conducted a content-centric review of blockchain-sustainability literature to identify the functions through which blockchain might contribute to various aspects of sustainability. Figure 1 explains various steps taken by the study to identify blockchain sustainability functions. Step A1 involved using the search string explained in Figure 1 to identify related documents via the systemic search of Web of Science and Scopus databases. Step A1 was conducted in November 2021. The advanced search in the initial search did not apply any specific limits, such as date range. The initial identification in step A1 resulted in the identification of 567 documents. Notably, the search string only focused on the "TITLE" domain to manage paper volume in a broad field, given that incorporating more domains could yield thousands of papers, affecting the study's reliability. To account for limitations that this decision might have caused, the study further used forward and backward review steps to identify papers that might have been omitted from the initial search due to the focus on the title domain.

Step A2 involved defining exclusion criteria. Following Ghobakhloo, Iranmanesh, et al. (2021), four exclusion criteria were defined to ensure the reliability of content-centric review outcomes (Figure 1). In step A3, the documents initially identified across step A1 were subjected to the exclusion criteria. As a result, 538 documents were excluded, and 29 articles were shortlisted as the initial pool of eligible articles. The backward review of the 29 eligible articles was conducted in step B1, in which documents cited by the eligible articles were identified and evaluated. Step B1 identified 103 additional related documents not identified in Step A1. The 103 newly identified documents were subjected to exclusion criteria in step B2. As a result, 95 documents were excluded, and 8 additional eligible articles were



Step A1: The initial identification
Objective: Identifying relevant documents within Scopus and Web of Science databases
Search string used in Scopus and Web of Science databases:
(TITLE (blockchain) OR TITLE ("Distributed ledger") AND TITLE (sustainable) OR TITLE (sustainability) OR TITLE (environment) OR TITLE (green) OR TITLE (circular))
Documents identified in stage A1 (n=567)

Step A2: Defining exclusion criteria
Exclusion criterion (EXC) 1: The document cannot be categorized as an article published in a reputable journal (e.g., book chapters).
Exclusion criterion 2: The article does not have its main body of text written in English.
Exclusion criterion 3: The article merely uses keywords such as *Blockchain* as a cited expression.
Exclusion criterion 4: The article does not explain how Blockchain may contribute to sustainability.

Step A3: Screening
Article removed due to EXC1 (n=219), EXC2 (n=36), EXC3 (n=44), and EXC4 (n=239)
Total number of articles excluded in step A3 (n=538)
Total number of eligible articles identified at step A3 (n=29)
The initial pool of eligible articles (n=29)

Step B1: Backward review
Going backward by reviewing the documents cited by the 29 articles identified in step A3 to determine prior *related* documents that require consideration.
Documents identified in step B1 (n=103)

Step B2: Screening
Article removed due to EXC1 (n=34), EXC2 (n=0), EXC3 (n=9), and EXC4 (n=52)
Total number of articles excluded step B2 (n=95)
Total number of eligible articles identified at step B2 (n=8)
The extended pool of eligible articles (n=29+8=37)

Step C1: Forward review
Going forward using Web of Science and Google Scholar to identify unchecked *related* documents citing the eligible articles identified across steps A3 and B2.
Journal articles identified in step C1 (n=86)

Step C2: Screening
Article removed due to EXC1 (n=39), EXC2 (n=1), EXC3 (n=15), and EXC4 (n=27)
Total number of articles excluded in step B2 (n=82)
Total number of eligible articles identified at step B2 (n=4)
The final pool of eligible articles (n=29+8+4=41)

Step D: Content Analysis
Content analysis of 41 eligible articles to identify Blockchain functions for sustainability

FIGURE 1 Content-centric review steps.

identified, leading to the extended pool of 37 (29 + 8) eligible articles. Step C1 involved conducting the forward review of the 33 eligible articles to identify related documents cited by them. Step C1 led to the identification of 86 related documents previously not identified across steps A1 and B1. In step C2, the newly identified 86 documents were subjected to the exclusion criteria, which excluded 82 ineligible documents and identified 4 additional eligible documents. Steps A1 to C2 led to the final pool of 41 (29 + 8 + 4) eligible articles.

The content assessment of the eligible articles was conducted in step D. Following existing guides (e.g., Ghobakhloo, Iranmanesh, et al., 2021; Webster & Watson, 2002), the research team developed and applied a comprehensive content analysis protocol to limit the thread of bias and increase the reliability of findings. Following the protocol, two assessors independently analyzed the content of eligible articles to identify blockchain functions for sustainability. The assessors used a standardized data archiving and management platform to ensure the traceability, comparability, and reliability of findings. Assessors also followed a detailed text denoising procedure to streamline the opinion summarization. As the final part of step D, the content assessors collaboratively reexamined their findings and took part in the disagreement tracking activity when needed. Step D identified 15 functions through which blockchain might contribute to developing various aspects of sustainability. Table 1 explains the acknowledgment of the functions across the eligible articles. Each of the 15 functions is explained in the following sections.

TABLE 1 Sustainability functions of blockchain, as identified within the literature.

Study	Sustainability function of blockchain														
	Business partner collaboration (BPC)	Corporate reputation (CPR)	Cost reduction (COR)	Manufacturing automation (MAA)	Pollution reduction and prevention (PRP)	Profit margin enhancement (PME)	Real-time information sharing (RIS)	Recycling and circularity improvement (RCI)	Resource consumption efficiency (RCE)	Structural decentralization (STD)	Traceability enhancement (TAE)	Transparency enhancement (TPE)	Trust development (TRD)	Value chain monitoring (VCM)	Value chain optimization (VCO)
Ajwani-Ramchandani et al. (2021)					x			x							x
Ali et al. (2021)						x					x			x	
Alves et al. (2022)				x			x	x		x	x				
Bakarich et al. (2020)											x	x	x		
Böckel et al. (2021)			x	x	x						x	x			x
Centobelli et al. (2022)											x	x	x		
Chaudhuri et al. (2021)	x										x	x	x		
Chen (2023)					x			x			x	x			
Calandra et al. (2023)			x		x	x			x	x			x		
Corrêa Tavares et al. (2021)			x							x	x	x	x		
Dal Mas et al. (2023)			x								x	x			
de Villiers et al. (2021)			x	x		x	x		x		x	x	x	x	
Di Vaio and Varriale (2020)	x						x					x			x
Erol et al. (2022)	x							x			x	x	x	x	
Esmaeilian et al. (2020)			x			x			x		x			x	
Friedman and Ormiston (2022)								x		x	x				
Gong et al. (2022)	x					x		x				x			
Guo et al. (2020)			x			x					x				
Jiang and Zheng (2021)					x										
Khan, Godil, et al. (2021)	x							x	x			x			
Khanfar et al. (2021)		x	x	x	x		x			x	x		x	x	x
Kleinknecht (2021)					x			x	x						
Kouhizadeh et al. (2020)	x	x					x				x	x	x		
Kshetri (2021)	x		x					x				x	x	x	
Kusi-Sarpong et al. (2022)					x			x	x		x	x			

(Continues)

TABLE 1 (Continued)

Study	Sustainability function of blockchain														
	Business partner collaboration (BPC)	Corporate reputation (CPR)	Cost reduction (COR)	Manufacturing automation (MAA)	Pollution reduction and prevention (PRP)	Profit margin enhancement (PME)	Real-time information sharing (RIS)	Recycling and circularity improvement (RCI)	Resource consumption efficiency (RCE)	Structural decentralization (STD)	Traceability enhancement (TAE)	Transparency enhancement (TPE)	Trust development (TRD)	Value chain monitoring (VCM)	Value chain optimization (VCO)
Leng et al. (2020)	x						x	x	x	x		x			x
Li et al. (2021)				x			x								
Mubarik et al. (2021)					x			x	x						
Najjar et al. (2023)							x				x	x			x
Nandi et al. (2021)							x			x					
Mukherjee et al. (2021)	x				x					x		x			
Nayal et al. (2021)	x				x		x	x	x		x		x	x	
Parmentola et al. (2022)					x			x	x						
Paul et al. (2021)	x											x	x		
Rana et al. (2021)		x	x							x	x	x			
Saberi et al. (2019)	x		x		x	x		x							
Schinckus (2020)	x				x		x	x						x	
Tiscini et al. (2020)								x		x	x				
Tomlinson et al. (2021)		x	x			x							x		x
Upadhyay et al. (2021)	x						x						x	x	
Yadav and Singh (2020)	x		x				x			x		x			

3.1 | Business partner collaboration

Collaboration is at the heart of any sustainability initiative for systematically tackling environmental and social challenges (Ghobakhloo, Iranmanesh, et al., 2021). It means companies should closely collaborate with their business partners and shareholders to address critical sustainability issues such as environmental degradation, inequality, climate change, and rebound effect (Esmaeilian et al., 2020). Blockchain fundamentally alters many aspects of business life, and it has become essential for promoting Business partner collaboration (BPC; Bai et al., 2020). Lumineau et al. (2021) believe that the contribution of blockchain to BPC involves restructuring three aspects of collaboration. First, blockchain's deterring effects, such as smart contracting, leave no room for dishonesty or reneging, expediting the partner selection procedures. Second, blockchain protocols cannot be readily revised. Thus, setting up blockchain has become a collective task, requiring the honest collaboration of business partners. Third, the autonomous execution and real-time information confirmation features of blockchain significantly decrease dishonesty and deviations in the execution phase of collaboration, increasing the efficiency and consistency of BPC (Lumineau et al., 2021).

3.2 | Corporate reputation

While the concept of corporate reputation (CPR) is highly debated, the stakeholder-centric view defines it as the aggregated feelings and opinions of stakeholders over the corporation (Quintana-García et al., 2021). CPR and sustainability appear to be mutually dependent. Sustainability improves CPR by increasing the stakeholders' acceptance of activities. Alternatively, more reputable businesses generally have more resources and strategic awareness to introduce sustainability into their operations (Gomez-Trujillo et al., 2020). Blockchain offers valuable opportunities to address the complexity and resource intensity of building CPR. The immutability and transparency of blockchain offer novel or complementary layers of trust to business operations (Boukis, 2020). Blockchain also strengthens CPR by increasing the transparency of the raw material used in manufacturing products and their carbon footprint. CPR is also improved by the smart contracting, decentralization, and transparency features of blockchain, which act as a weapon against unfair wages, child labor abuse, or poor working conditions (Centobelli et al., 2022; Senou et al., 2019).

3.3 | Cost reduction

Promoting sustainability is resource-intensive, and reducing operating costs is critical for businesses seeking sustainability (Ching et al., 2022). Thus, cost reduction (COR) would allow businesses to prioritize the implementation of more resource-efficient, energy-aware, and human-centric operations technologies and practices (Ghobakhloo, Fathi, et al., 2021). Blockchain offers the COR function in various ways. This technology significantly reduces the information variability of supply chain operations, leading to more precise production planning, improved delivery time, reduced warehousing costs, and logistics expenses (Wamba et al., 2020). Hald and Kinra (2019) further believe that blockchain technology improves supply partners' performance and reduces their operating costs through improving supply chain capabilities (e.g., process integration or strategic planning) and allowing business partners to better leverage their business intelligence and supply chain management skills. More importantly, blockchain can increase manufacturing cost efficiency by enabling energy accounting and better asset management in smart factories (Ghobakhloo & Iranmanesh, 2021).

3.4 | Manufacturing automation

Manufacturing automation (MAA) involves using advanced operations and digital technologies to automate production processes and decentralize manufacturing decision processes. MAA has become a strategic priority under the disruptive force of Industry 4.0 (Ghobakhloo, Fathi, et al., 2021). The literature has widely documented the contribution of MAA to sustainability (Amjad et al., 2021). A safer/smarter working environment, resource efficiency, energy awareness, emission reduction, reduced rework, and higher product quality are among the contributions of MAA to sustainability (Ching et al., 2022). The role of blockchain in delivering the MAA function is twofold. As a crucial technological constituent of the Industrial Internet of Things (IIoT) and Cyber-Physical Production Systems (CPPSs), blockchain supports decentralized intelligence and offers a more reliable, safer, and integrated substructure for the autonomous operation of manufacturing systems (Lee et al., 2019). Second, blockchain features such as smart contracting and security increase the efficiency of computer-integrated manufacturing methods, particularly additive manufacturing, by minimizing the data bridge threat for CAD models or ensuring real-time monitoring of product design compliance (Ghimire et al., 2021).

3.5 | Pollution reduction and prevention

Pollution reduction and prevention (POR) have long been recognized as critical sustainability requirements (Elleuch et al., 2018). Pollution can originate from any human activity. In the industrial scenario, most supply chain processes, from raw material extraction to the production and consumption of the final products, can generate pollution (Sim & Kim, 2021). POR function involves minimizing pollution or even preventing it by introducing smarter and more efficient operations or innovative business models (Elleuch et al., 2018). Blockchain delivers the POR function by ensuring that supply partners adhere to the mandatory pollution prevention standards and requirements (Bai et al., 2020). In particular, blockchain enhances the traceability, visibility, and verifiability of products' carbon footprint. These features allow POR strategies to be introduced into the material, production design, supplier, distribution channels, and vendor selection decision processes (Wang et al., 2020). Experts also believe decentralized automation, the critical outcome of institutionalizing blockchain, offers practical implications for POR strategies. More importantly, the contribution of blockchain to renewable energy diffusion and blockchain-based energy trading, and the resulting energy efficiency, are valuable to POR (Tsao & Thanh, 2021).

3.6 | Profit margin enhancement

Businesses require access to the necessary financial resources to prioritize sustainability. Businesses consider sustainability expensive for several reasons, such as the premium prices of environmentally friendly raw materials, the complexity of integrating renewables, or the implementation of equitable business operations and practices (Ching et al., 2022). Using cost-minimization techniques, such as implementing proprietary technologies and the resulting profit margin improvement, allows businesses to promote sustainability and endure costs (Yadav et al., 2020). Blockchain enables profit margin enhancement (PME) to function in various ways. First, blockchain is revolutionizing the concept of financial flow and transactions within supply chains. For example, blockchain reduces the cost of transactions by removing the trusted third party from supply chain financial flows (Schmidt & Wagner, 2019). Second, the data sharing, variability, and decentralization features of blockchain reduce the cost of collaboration, information sharing, and asset tracking across the supply chain and service management operations (Centobelli et al., 2022). More importantly, blockchain can deliver the PME function by facilitating business model innovation or reinvention. For example, manufacturing companies that rely on differentiation or focus strategies can integrate blockchain with other disruptive technologies such as IIoT to move toward the Manufacturing-as-a-Service business model. By doing so, they can maximize their profit margin by renting out their manufacturing capability and maximizing the usage and profitability of the installed production capacity (Wang et al., 2021).

3.7 | Real-time information sharing

The use of shared information systems for accumulating, sharing, and using socioeconomic and socio-environmental data and information is critical to sustainable production and consumption (Ching et al., 2022; Helo & Shamsuzzoha, 2020). Under such circumstances, RIS allows decision-makers to quickly and reliably access diverse data sources and computational capabilities to convey the resulting insight into favorable actions toward sustainability (Tiwari & Khan, 2020). While cloud technologies, edge computing, and the IoT serve as primary constituents of a real-time information-sharing system, blockchain is indispensable for the security and authenticity of such a system (Helo & Shamsuzzoha, 2020). Blockchain offers a distributed P2P communication network where business partners can share sustainability data and performance indices with minimum concerns over losing data control or ownership (Li et al., 2021). The decentralization feature of blockchain ensures that each node verifies data transactions, increasing the scalability and transparency of real-time data exchange and incentivizing business partners to share sustainability data in real-time (Di Vaio & Varriale, 2020).

3.8 | Recycling and circularity improvement

Recycling and circularity are important frontiers of sustainability (Upadhyay et al., 2021). Recycling involves reusing materials used already so that recycled material can be used in new products, and waste can be prevented. Recycling is crucial to preventing the acceleration of environmental degradation (Tabelin et al., 2021). Circularity or circular economy represents the proactive efforts for introducing sustainability into production and consumption. Circularity contributes to sustainability via several principles, such as eco-friendly product design, refurbishing, repurposing, and remanufacturing (Kouhizadeh et al., 2020). The enabling role of blockchain concerning the recycling and circularity improvement (RCI) function is threefold. First, integrating blockchain with Artificial Intelligence (AI), cloud computing, and IoT creates a hyperconnected value chain ecosystem that increases the productivity of industrial operations and minimizes waste, defects, and hazardous accidents (Li et al., 2021). Second, the traceability and transparency capabilities of blockchain push supply partners to adhere to their circularity responsibilities, such as renewable integration (Upadhyay et al., 2021). Third, the information reliability and transparency features of blockchain lead to resource utilization optimization across the value chain, enhancing the efficiency of redesigning, remanufacturing, recycling, and repairing activities (Nandi et al., 2021).

3.9 | Resource consumption efficiency

Resource efficiency is essential for sustainable growth, which involves gaining more value from Earth's limited resources and limiting adverse environmental impacts (Diaz Lopez et al., 2019). Blockchain delivers the resource consumption efficiency (RCE) function in a variety of manners. Blockchain increases the efficiency of manufacturing operations by empowering trusted data exchange and automating workflow across manufacturing chains (Zuo, 2021). The resulting production planning, control, and management efficiencies improve logistics, inventory management, and equipment reliability, leading to waste prevention and resource efficiency (Ching et al., 2022; Leng et al., 2020). Second, the extended visibility of blockchain reduces the complexity of supply chain management operations, for example, by removing manual certification and approval (Wamba et al., 2020). As a result, supply chains can better deal with improperly sourced raw materials, bottlenecks, risk points, product or process design inefficiencies, and even counterfeiting, which result in valuable resource efficiency opportunities across the value networks (Leng et al., 2020).

3.10 | Structural decentralization

Structural decentralization (STD) function involves transferring decision-making controls from centralized units to distributed networks in the blockchain context (Zutshi et al., 2021). This feature can offer invaluable opportunities for promoting the economic and socio-environmental pillars of sustainability. In most traditional value chains, the financial and data interactions among upstream suppliers and the downstream consumers are entrenched by third-party aggregators-distributors (Dutra et al., 2018). Nonetheless, the decentralization feature of blockchain allows the P2P data networking of value chain partners, removing the role of monopolistic aggregators-distributors when needed (Li et al., 2018). As a result, supply chains and their stakeholders can enjoy more impartial economic opportunities and efficiencies (Schinckus, 2020). Thanks to blockchain, the equitable distribution of income across value chains offers essential opportunities for financing the integration of cleaner production technologies, sustainable business model innovation, or recruitment of sustainability talents (Bai et al., 2020).

3.11 | Traceability enhancement

Viewed from the supply chain management perspective, traceability refers to the process of tracking the movement of products and their components all across the value chain and through their entire life cycle, from raw material and energy extraction to their end-use (Hastig & Sodhi, 2020). Traceability is indispensable to sustainability, as it allows supply partners to entrench sustainable thinking into their decision-making process directly (Centobelli et al., 2022). In particular, the ability to trace materials during the entire product life cycle is vital to the conversion processes that enable reusing, remanufacturing, recycling, and repurposing pillars of circularity (Agrawal et al., 2021). Blockchain promotes the traceability enhancement (TAE) function in various ways. For example, blockchain enhances the verifiability and tamper-resistance of supply chain data via developing an immutable ledger. The smart contracting feature can also streamline many aspects of supply chain traceability processes (Esmaeilian et al., 2020). Blockchain can create an audit trail of all supply chain transactions, from raw materials procurement to delivery logistics (Bai et al., 2020). Overall, the traceability feature of blockchain promotes the sustainability of supply chain operations via restricting illegal practices (e.g., forced child labor), streamlining sustainability performance monitoring, and simplifying coordination for introducing circularity (Hastig & Sodhi, 2020).

3.12 | Transparency enhancement

Transparency requires focal supply partners to be accurately aware of what is happening throughout their supply chains, such as the environmental impact of operations and logistics, and disseminate this knowledge to all stakeholders (Bai et al., 2020). The contribution of supply chain transparency to sustainability is well-documented. According to Gardner et al.'s (2019) transparency-sustainability framework, reducing supply chain complexity, risk mitigation, operational improvements, and environmental performance assessment are examples of functions through which transparency promotes sustainability. Blockchain excels in delivering the transparency enhancement (TPE) function by increasing the efficiency, accuracy, and accessibility of supply chain information (Centobelli et al., 2022). Blockchain complements other technological constituents of Industry 4.0, such as IoT, to allow businesses to create a digital replica of their operations and practices (Ghobakhloo, Fathi, et al., 2021). The resulting decentralized and immutable records of operations, transactions, material records, outsourcing contracts, and product environmental footprint can be crucial to supply chain transparency (Venkatesh et al., 2020).

3.13 | Trust Development

Sustainable partnership and collaboration begin with trust among supply partners (Howson, 2020). Therefore, authentic partnership and the resulting trust-based supplier collaboration and customer relationship are indispensable to fostering sustainability (Centobelli et al., 2022). Building trust is complicated, especially across complex, multi-tier, and global supply chains, requiring complete transparency, responsible collaboration, visibility, and shared empathy (Mahyuni et al., 2020). Blockchain delivers the trust development (TRD) function by addressing some of the fundamental requirements of trust across supply chains. The smart contracting feature of blockchain can ensure all participants that agreements are executed autonomously when necessary conditions are met (Tosh et al., 2019). Since transactions are encrypted, and no third parties are involved in smart contracts, all partners can trust the authenticity of business interactions (Esmaeilian et al., 2020). Blockchain also increases the efficiency and accuracy of supply chain interactions. The resulting time and cost savings can encourage supply partners to move toward responsible collaboration (Centobelli et al., 2022). More importantly, blockchain promotes trust by increasing the security and dependability of information sharing among business partners and addressing data provenance and ownership concerns (Agrawal et al., 2021; Tosh et al., 2019).

3.14 | Value chain monitoring

Effective value chain monitoring (VCM) offers irrefutable benefits to sustainability. Value chain monitoring involves applying data analytics solutions to manage and control upstream suppliers' operations, production infrastructure, warehousing processes, logistics, and overall supply chain operations management (Júnior et al., 2022). Value chain monitoring promotes sustainability by enabling the value chain-wide identification of sustainability issues, supply chain mapping, environmental opportunity sensing, tracking of environmental footprint, and sustainability performance measurement (Kumar et al., 2021). Blockchain enables the VCM function by reducing the complexity of monetary transactions and information flow (Di Vaio & Varriale, 2020; Schmidt & Wagner, 2019). Complex supply chains nowadays draw on

IoT and machine learning to monitor and track the relevant aspects of the supply chain, and blockchain ensures the reliability and trustworthiness of the data used for these purposes (Centobelli et al., 2022). Blockchain also improves the monitoring of procurement and outsourcing operations by streamlining smart tendering throughout the supply chain (Rane & Thakker, 2020). The immutability of blockchain also ensures that the accountability and compliance of value chain members are reliably monitored (Friedman & Ormiston, 2022).

3.15 | Value chain optimization

Value chain optimization (VCO) refers to businesses strategically adjusting their processes to gain more optimal outcomes within their value chain. VCO involves various strategic adjustments such as value leak reduction, deeper collaborations, product or process innovation, and inefficiencies elimination (Shabani et al., 2013). Consistently, VCO promotes sustainability via material efficiency, waste reduction, higher equipment effectiveness, lower energy consumption, and overall operational efficiency (Chávez et al., 2018). Blockchain delivers the VCO function by reducing paperwork, autonomous data authentication, data accessibility, and improved decision-making (Bai et al., 2020; Esmaeilian et al., 2020). For example, retailers use blockchain to track grocery products optimally and minimize spoilage. Alternatively, using blockchain for the virtualized and tamperproof bill of lading can automate the entire order tracking and cargo ownership transferring processes, thus, optimizing logistics and transportation (Koh et al., 2020). The use of smart contracts and data immutably of blockchain significantly optimizes the shipping and fulfillment processes and reduces the costs of auditing, accounting, and compliance assessment (De Giovanni, 2020).

4 | ISM METHODOLOGY

ISM is a well-known method of identifying the contextual relationships among complex system components. ISM involves the iterative and systemic application of graph theory to turn experts' opinions regarding the pairwise relationships of the components into graphical representations of the underlying complex phenomenon (Yadav et al., 2021). Previous studies have extensively used ISM to understand the sustainability implications of technological innovation. Examples include using ISM to identify Industry 4.0 implications for sustainable energy (Ghobakhloo & Fathi, 2021) or model IoT contributions to sustainable supply chain management in agriculture (Yadav et al., 2021). The present study follows the ISM literature (e.g., Ching et al., 2022) and applies the ISM using the steps shown in Figure 2. These steps are explained in the following sections.

4.1 | Collecting experts' opinion

ISM is interpretive in the sense that experts' judgments are used to explain whether and how the components of a system are sequentially interrelated (Ching et al., 2022). The present study collected the opinions of eight experts for ISM analysis. The research team drew on the existing guides (e.g., Hertzum, 2014) and implemented a robust protocol to ensure the reliability of expert selection and opinion collection procedures. First, the research team collaborated with the academic and industry partners to identify suitable experts knowledgeable enough to participate in the study. This collaboration identified 25 experts across Europe, Australia, and South East Asia, potentially knowledgeable to participate. Experts identified were contacted and informed about the nature of the study in early October 2021 and further invited to participate in the briefing meeting. Twelve experts did not agree to participate. Following Ghobakhloo and Fathi's (2021) procedure, the research team interviewed the remaining 13 experts to ensure they had the necessary cognitive and communication skills to participate in the expert panel meetings. This procedure led to shortlisting eight experts to participate in the expert panel meetings. The process of expert opinion collection was done during five consecutive expert panel meetings held in January 2022, within which the research team employed the Nominal Group Technique (NGT) to organize the experts' interactions. Meetings one and two focused on refining and validating the blockchain sustainability functions identified by the research team. The expert panel mostly agreed with the structure and description of blockchain sustainability functions, requesting some improvements to the titling and description of the functions identified and presented by the research team. Across the remaining meetings, the expert panel collectively identified the pairwise relationships among the 15 blockchain sustainability functions.

Overall, the research team applied multiple measures to minimize respondent biases and enhance both the reliability and validity of the data collection process. The selection of experts was a meticulously planned endeavor, incorporating detailed criteria, pre-survey training, diversity in expertise, and robust interviews, which collectively reduced the risk of participant bias and ensured that panel members had the necessary qualifications to contribute effectively. The deliberate shortlisting of the most qualified experts further mitigated potential biases that may have arisen from less-qualified or less-informed participants. To bolster data reliability and validity, the study employed a structured and comprehensive opinion collection process through consecutive expert panel meetings, which were a vital component of the data collection procedure. The use of the NGT within these meetings helped minimize dominant voices and biases, ensuring that all expert opinions were considered equally. Various data collection measures, such as controlled moderation and round-robin opinion recording, were implemented to diminish the potential for opinion invisibility and bias. Peer debriefing and external feedback from scholars not involved in the study further contributed to the study's validity. The validation of results with the expert panel post-analysis ensured that the findings accurately represented their opinions. These combined efforts have significantly reduced the risk of bias, enhanced data reliability, and validated the study's outcomes.

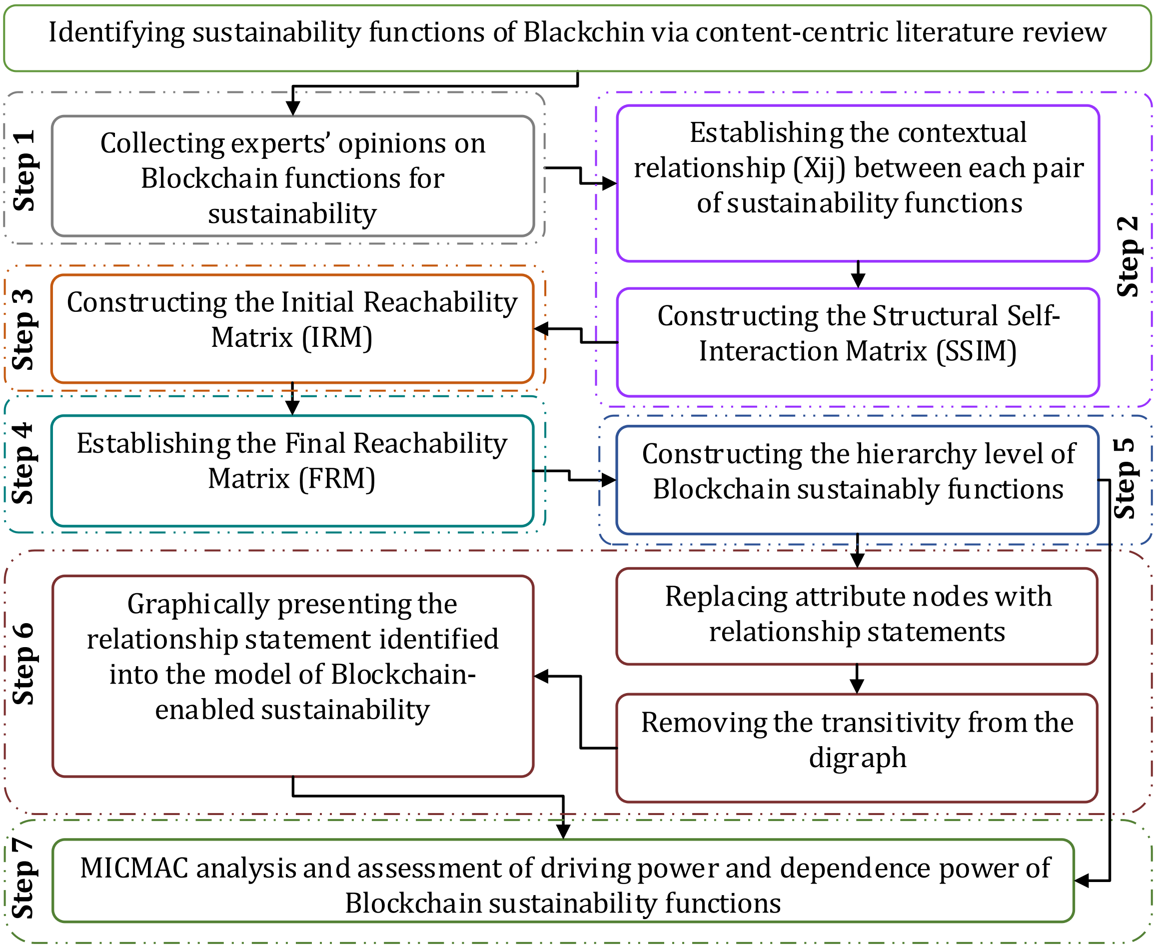


FIGURE 2 ISM method and underlying steps applied in the study.

4.2 | Establishing contextual relationships

This step involves using the following coding system to identify contextual relationships among each pair of functions and develop the Structural Self-Interaction Matrix (SSIM). Building on the following coding system, the SSIM of the present study is established in Table 2. For instance, the MAA-RIS pairwise relationship is coded by X in Table 2, meaning MAA and RIS functions of blockchain cause each other.

4.3 | Constructing IRM

Constructing the Initial Reachability Matrix (IRM) involves applying the following conversion scheme to the SSIM. By subjecting the SSIM of the study to the following conversion scheme, the IRM is constructed in Table 3.

> If *(i, j)* entry in the SSIM is coded V, then entry *(i, j)* in the IRM should be set to 1, and entry *(j, i)* should be set to 0.
>
> If *(i, j)* entry in the SSIM is coded A, then entry *(i, j)* in the IRM should be set to 0, and entry *(j, i)* should be set to 1.
>
> If *(i, j)* entry in the SSIM is coded X, both *(i, j)* and *(j, i)* entries in the IRM should be set to 1.
>
> If *(i, j)* entry in the SSIM is coded as O, both *(i, j)* and *(j, i)* entries in the IRM should be set to 0.

4.4 | Constructing FRM

Constructing the Final Reachability Matrix (FRM) involves subjecting the pairwise relationships established in the IRM to the *Transitivity* rule. This rule implies that if factor *X* causes factor *Y* and factor *Y* causes factor *Z*, then factor *X* is inadvertently the determinant of factor *Z*, regardless of their direct causal relationship (Yadav et al., 2021). The existence of transitivity is symbolized by 1* in the FRM. For example, the BPC-CPR entry in the IRM is 0, meaning these functions are independent. However, BPC directly causes RCI (BPC-RCI entry in Table 2 is 1), and RCI directly causes CPR (RCI-CPR entry in Table 2 is 1). Consistently, and drawing on the transitivity rule, the BPC-CPR entry in FRM of the study (Table 3) is represented by 1*. Table 4 also represents the driving power and dependence power of each sustainability function. The driving power for a given function is calculated as the number of functions caused by

TABLE 2 The structural self-interaction matrix.

	VCO	VCM	TRD	TPE	TAE	STD	RCE	RCI	RIS	PME	POR	MAA	COR	CPR	BPC
BPC	V	O	A	O	O	O	V	V	A	O	O	A	O	O	–
CPR	O	A	O	A	A	O	V	X	O	V	X	O	O	–	
COR	A	O	O	O	O	O	A	A	O	V	O	A	–		
MAA	V	V	V	V	V	A	V	O	X	O	O	–			
POR	O	A	O	O	O	O	A	A	O	V	–				
PME	A	O	O	O	O	O	A	A	O	–					
RIS	V	V	V	V	O	A	O	V	–						
RCI	O	A	O	A	A	A	V	–							
RCE	A	A	O	O	A	O	–								
STD	O	O	V	V	V	–									
TAE	V	V	V	V	–										
TPE	O	V	V	–											
TRD	O	A	–												
VCM	O	–													
VCO	–														

Abbreviations: A, blockchain sustainability function *i* is caused by blockchain sustainability function *j*; O, blockchain sustainability functions *i* and *j* are independent; V, blockchain sustainability function *i* causes blockchain sustainability function *j*; X, blockchain sustainability functions *i* and *j* cause each other.

TABLE 3 The initial reachability matrix.

	BPC	CPR	COR	MAA	POR	PME	RIS	RCI	RCE	STD	TAE	TPE	TRD	VCM	VCO
BPC	1	0	0	0	0	0	0	1	1	0	0	0	0	0	1
CPR	0	1	0	0	1	1	0	1	1	0	0	0	0	0	0
COR	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0
MAA	1	0	1	1	0	0	1	0	1	0	1	1	1	1	1
POR	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0
PME	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
RIS	1	0	0	1	0	0	1	1	0	0	0	1	1	1	1
RCI	0	1	1	0	1	1	0	1	1	0	0	0	0	0	0
RCE	0	0	1	0	1	1	0	0	1	0	0	0	0	0	0
STD	0	0	0	1	0	0	1	1	0	1	1	1	1	0	0
TAE	0	1	0	0	0	0	0	1	1	0	1	1	1	1	1
TPE	0	1	0	0	0	0	0	1	0	0	0	1	1	1	0
TRD	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0
VCM	0	1	0	0	1	0	0	1	1	0	0	0	1	1	0
VCO	0	0	1	0	0	1	0	0	1	0	0	0	0	0	1

it. Alternatively, driving power for a given function is calculated as the number of functions caused by. The implications of driving power and dependence power for building the MICMAC matrix will be explained in the following sections.

4.5 | Constructing hierarchy levels

Constructing hierarchy levels of blockchain sustainability functions involves drawing on FRM to develop each function's reachability, antecedent, and intersection sets. The reachability set for a particular function consists of functions reached (or caused) by it, whereas functions causing (or determining) the particular function construct the antecedent set. Functions shared among both reachability and antecedent sets of a given function construct the intersection set. After constructing the reachability, antecedent, and intersection sets for all functions, the hierarchy levels can be established by executing the extraction procedure. The extraction procedure involves identifying the functions with identical reachability and intersection sets in each iteration and removing them from the successive iterations of

TABLE 4 The final reachability matrix.

	BPC	CPR	COR	MAA	POR	PME	RIS	RCI	RCE	STD	TAE	TPE	TRD	VCM	VCO	Driving power	Rank
BPC	1	1*	1*	0	1*	1*	0	1	1	0	0	0	0	0	1	8	*6*
CPR	0	1	1*	0	1	1	0	1	1	0	0	0	0	0	0	6	*7*
COR	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	2	*9*
MAA	1	1*	1	1	1*	1*	1	1*	1	0	1	1	1	1	1	14	*2*
POR	0	1	0	0	1	1*	0	1*	1*	0	0	0	0	0	0	5	*8*
PME	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	*10*
RIS	1	1*	1*	1	1*	1*	1	1	1*	0	1*	1	1	1	1	14	*2*
RCI	0	1	1	0	1	1	0	1	1	0	0	0	0	0	0	6	*7*
RCE	0	1*	1	0	1	1	0	0	1	0	0	0	0	0	0	5	*8*
STD	1*	1*	1*	1	1*	1*	1	1	1*	1	1	1	1	1*	1*	15	*1*
TAE	1*	1	1*	0	1*	1*	0	1	1	0	1	1	1	1	1	12	*3*
TPE	1*	1	1*	0	1*	1*	0	1	1*	0	0	1	1	1	0	10	*4*
TRD	1	0	0	0	0	0	0	1*	1*	0	0	0	1	0	1*	5	*8*
VCM	1*	1	1*	0	1	1*	0	1	1	0	0	0	1	1	0	9	*5*
VCO	0	0	1	0	1*	1	0	0	1	0	0	0	0	0	1	5	*8*
Dependence power	8	11	12	3	12	14	3	11	13	1	4	5	7	6	7		
Rank	*5*	*4*	*3*	*10*	*3*	*1*	*10*	*4*	*2*	*11*	*9*	*8*	*6*	*7*	*6*		

TABLE 5 Hierarchy level for blockchain sustainability functions.

Factors	Reachability set	Antecedent set	Intersection set	Level
Iteration I				
BPC	BPC, CPR, COR, POR, PME, RCI, RCE, VCO	BPC, MAA, RIS, STD, TAE, TPE, TRD, VCM	BPC	
CPR	CPR, COR, POR, PME, RCI, RCE	BPC, CPR, MAA, POR, RIS, RCI, RCE, STD, TAE, TPE, VCM	CPR, POR, RCI, RCE	
COR	COR, PME	BPC, CPR, COR, MAA, RIS, RCI, RCE, STD, TAE, TPE, VCM, VCO	COR	
MAA	BPC, CPR, COR, MAA, POR, PME, RIS, RCI, RCE, TAE, TPE, TRD, VCM, VCO	MAA, RIS, STD	MAA, RIS	
POR	CPR, POR, PME, RCI, RCE	BPC, CPR, MAA, POR, RIS, RCI, RCE, STD, TAE, TPE, VCM, VCO	CPR, POR, RCI, RCE	
PME	PME	BPC, CPR, COR, MAA, POR, PME, RIS, RCI, RCE, STD, TAE, TPE, VCM, VCO	PME	*I*
RIS	BPC, CPR, COR, MAA, POR, PME, RIS, RCI, RCE, TAE, TPE, TRD, VCM, VCO	MAA, RIS, STD	MAA, RIS	
RCI	CPR, COR, POR, PME, RCI, RCE	BPC, CPR, MAA, POR, RIS, RCI, STD, TAE, TPE, TRD, VCM	CPR, POR, RCI	
RCE	CPR, COR, POR, PME, RCE	BPC, CPR, MAA, POR, RIS, RCI, RCE, STD, TAE, TPE, TRD, VCM, VCO	CPR, POR, RCE	
STD	BPC, CPR, COR, MAA, POR, PME, RIS, RCI, RCE, STD, TAE, TPE, TRD, VCM, VCO	STD	STD	
TAE	BPC, CPR, COR, POR, PME, RCI, RCE, TAE, TPE, TRD, VCM, VCO	MAA, RIS, STD, TAE	TAE	
TPE	BPC, CPR, COR, POR, PME, RCI, RCE, TPE, TRD, VCM	MAA, RIS, STD, TAE, TPE	TPE	
TRD	BPC, RCI, RCE, TRD, VCO	MAA, RIS, STD, TAE, TPE, TRD, VCM	TRD	
VCM	BPC, CPR, COR, POR, PME, RCI, RCE, TRD, VCM	MAA, RIS, STD, TAE, TPE, VCM	VCM	
VCO	COR, POR, PME, RCE, VCO	BPC, MAA, RIS, STD, TAE, TRD, VCO	VCO	
Iteration II				
BPC	BPC, CPR, COR, POR, RCI, RCE, VCO	BPC, MAA, RIS, STD, TAE, TPE, TRD, VCM	BPC	
CPR	CPR, COR, POR, RCI, RCE	BPC, CPR, MAA, POR, RIS, RCI, RCE, STD, TAE, TPE, VCM	CPR, POR, RCI, RCE	
COR	COR	BPC, CPR, COR, MAA, RIS, RCI, RCE, STD, TAE, TPE, VCM, VCO	COR	*II*
MAA	BPC, CPR, COR, MAA, POR, RIS, RCI, RCE, TAE, TPE, TRD, VCM, VCO	MAA, RIS, STD	MAA, RIS	
POR	CPR, POR, RCI, RCE	BPC, CPR, MAA, POR, RIS, RCI, RCE, STD, TAE, TPE, VCM, VCO	CPR, POR, RCI, RCE	*II*
RIS	BPC, CPR, COR, MAA, POR, RIS, RCI, RCE, TAE, TPE, TRD, VCM, VCO	MAA, RIS, STD	MAA, RIS	
RCI	CPR, COR, POR, RCI, RCE	BPC, CPR, MAA, POR, RIS, RCI, STD, TAE, TPE, TRD, VCM	CPR, POR, RCI	
RCE	CPR, COR, POR, RCE	BPC, CPR, MAA, POR, RIS, RCI, RCE, STD, TAE, TPE, TRD, VCM, VCO	CPR, POR, RCE	
STD	BPC, CPR, COR, MAA, POR, RIS, RCI, RCE, STD, TAE, TPE, TRD, VCM, VCO	STD	STD	
TAE	BPC, CPR, COR, POR, RCI, RCE, TAE, TPE, TRD, VCM, VCO	MAA, RIS, STD, TAE	TAE	
TPE	BPC, CPR, COR, POR, RCI, RCE, TPE, TRD, VCM	MAA, RIS, STD, TAE, TPE	TPE	
TRD	BPC, RCI, RCE, TRD, VCO	MAA, RIS, STD, TAE, TPE, TRD, VCM	TRD	
VCM	BPC, CPR, COR, POR, RCI, RCE, TRD, VCM	MAA, RIS, STD, TAE, TPE, VCM	VCM	
VCO	COR, POR, RCE, VCO	BPC, MAA, RIS, STD, TAE, TRD, VCO	VCO	

TABLE 5 (Continued)

Factors	Reachability set	Antecedent set	Intersection set	Level
Iteration III				
BPC	BPC, CPR, RCI, RCE, VCO	BPC, MAA, RIS, STD, TAE, TPE, TRD, VCM	BPC	
CPR	CPR, RCI, RCE	BPC, CPR, MAA, RIS, RCI, RCE, STD, TAE, TPE, VCM	CPR, RCI, RCE	*III*
MAA	BPC, CPR, MAA, RIS, RCI, RCE, TAE, TPE, TRD, VCM, VCO	MAA, RIS, STD	MAA, RIS	
RIS	BPC, CPR, MAA, RIS, RCI, RCE, TAE, TPE, TRD, VCM, VCO	MAA, RIS, STD	MAA, RIS	
RCI	CPR, RCI, RCE	BPC, CPR, MAA, RIS, RCI, STD, TAE, TPE, TRD, VCM	CPR, RCI	
RCE	CPR, RCE	BPC, CPR, MAA, RIS, RCI, RCE, STD, TAE, TPE, TRD, VCM, VCO	CPR, RCE	*III*
STD	BPC, CPR, MAA, RIS, RCI, RCE, STD, TAE, TPE, TRD, VCM, VCO	STD	STD	
TAE	BPC, CPR, RCI, RCE, TAE, TPE, TRD, VCM, VCO	MAA, RIS, STD, TAE	TAE	
TPE	BPC, CPR, RCI, RCE, TPE, TRD, VCM	MAA, RIS, STD, TAE, TPE	TPE	
TRD	BPC, RCI, RCE, TRD, VCO	MAA, RIS, STD, TAE, TPE, TRD, VCM	TRD	
VCM	BPC, CPR, RCI, RCE, TRD, VCM	MAA, RIS, STD, TAE, TPE, VCM	VCM	
VCO	RCE, VCO	BPC, MAA, RIS, STD, TAE, TRD, VCO	VCO	
Iteration IV				
BPC	BPC, RCI, VCO	BPC, MAA, RIS, STD, TAE, TPE, TRD, VCM	BPC	
MAA	BPC, MAA, RIS, RCI, TAE, TPE, TRD, VCM, VCO	MAA, RIS, STD	MAA, RIS	
RIS	BPC, MAA, RIS, RCI, TAE, TPE, TRD, VCM, VCO	MAA, RIS, STD	MAA, RIS	
RCI	RCI	BPC, MAA, RIS, RCI, STD, TAE, TPE, TRD, VCM	RCI	*IV*
STD	BPC, MAA, RIS, RCI, STD, TAE, TPE, TRD, VCM, VCO	STD	STD	
TAE	BPC, RCI, TAE, TPE, TRD, VCM, VCO	MAA, RIS, STD, TAE	TAE	
TPE	BPC, RCI, TPE, TRD, VCM	MAA, RIS, STD, TAE, TPE	TPE	
TRD	BPC, RCI, TRD, VCO	MAA, RIS, STD, TAE, TPE, TRD, VCM	TRD	
VCM	BPC, RCI, TRD, VCM	MAA, RIS, STD, TAE, TPE, VCM	VCM	
VCO	VCO	BPC, MAA, RIS, STD, TAE, TRD, VCO	VCO	*IV*
Iteration V				
BPC	BPC	BPC, MAA, RIS, STD, TAE, TPE, TRD, VCM	BPC	*V*
MAA	BPC, MAA, RIS, TAE, TPE, TRD, VCM	MAA, RIS, STD	MAA, RIS	
RIS	BPC, MAA, RIS, TAE, TPE, TRD, VCM	MAA, RIS, STD	MAA, RIS	
STD	BPC, MAA, RIS, STD, TAE, TPE, TRD, VCM	STD	STD	
TAE	BPC, TAE, TPE, TRD, VCM	MAA, RIS, STD, TAE	TAE	
TPE	BPC, TPE, TRD, VCM	MAA, RIS, STD, TAE, TPE	TPE	
TRD	BPC, TRD	MAA, RIS, STD, TAE, TPE, TRD, VCM	TRD	
VCM	BPC, TRD, VCM	MAA, RIS, STD, TAE, TPE, VCM	VCM	
Iteration VI				
MAA	MAA, RIS, TAE, TPE, TRD, VCM	MAA, RIS, STD	MAA, RIS	
RIS	MAA, RIS, TAE, TPE, TRD, VCM	MAA, RIS, STD	MAA, RIS	
STD	MAA, RIS, STD, TAE, TPE, TRD, VCM	STD	STD	
TAE	TAE, TPE, TRD, VCM	MAA, RIS, STD, TAE	TAE	
TPE	TPE, TRD, VCM	MAA, RIS, STD, TAE, TPE	TPE	
TRD	TRD	MAA, RIS, STD, TAE, TPE, TRD, VCM	TRD	*VI*
VCM	TRD, VCM	MAA, RIS, STD, TAE, TPE, VCM	VCM	
Iteration VII				
MAA	MAA, RIS, TAE, TPE, VCM	MAA, RIS, STD	MAA, RIS	

(Continues)

TABLE 5 (Continued)

Factors	Reachability set	Antecedent set	Intersection set	Level
RIS	MAA, RIS, TAE, TPE, VCM	MAA, RIS, STD	MAA, RIS	
STD	MAA, RIS, STD, TAE, TPE, VCM	STD	STD	
TAE	TAE, TPE, VCM	MAA, RIS, STD, TAE	TAE	
TPE	TPE, VCM	MAA, RIS, STD, TAE, TPE	TPE	
VCM	VCM	MAA, RIS, STD, TAE, TPE, VCM	VCM	*VII*
Iteration VIII				
MAA	MAA, RIS, TAE, TPE	MAA, RIS, STD	MAA, RIS	
RIS	MAA, RIS, TAE, TPE	MAA, RIS, STD	MAA, RIS	
STD	MAA, RIS, STD, TAE, TPE	STD	STD	
TAE	TAE, TPE	MAA, RIS, STD, TAE	TAE	
TPE	TPE	MAA, RIS, STD, TAE, TPE	TPE	*VIII*
Iteration IX				
MAA	MAA, RIS, TAE	MAA, RIS, STD	MAA, RIS	
RIS	MAA, RIS, TAE	MAA, RIS, STD	MAA, RIS	
STD	MAA, RIS, STD, TAE	STD	STD	
TAE	TAE	MAA, RIS, STD, TAE	TAE	*IX*
Iteration X				
MAA	MAA, RIS	MAA, RIS, STD	MAA, RIS	*X*
RIS	MAA, RIS	MAA, RIS, STD	MAA, RIS	*X*
STD	MAA, RIS, STD	STD	STD	
Iteration XI				
STD	STD	STD	STD	*XI*

extraction procedures. For example, Table 5 shows that PME is the only function with identical reachability and intersection sets for iteration I. Thus, PME is removed from all the remaining reachability, antecedent, and intersection sets, and the extraction procedure is continued iteratively until the hierarchy level for each blockchain sustainability function is determined successively.

4.6 | The interpretive blockchain-enabled sustainability model

Figure 3 represents the interpretive structural model of blockchain-enabled sustainability. This model has been constructed based on the hierarchy level of sustainability functions identified in Table 5. Since the hierarchy level of functions was identified across 11 iterations, the ISM-based model in Figure 3 consists of 11 placement levels. However, following the ISM standard procedure, the placement order in Figure 3 is the opposite of the extraction sequence in Table 5. For example, the STD function extracted in iteration 11 takes the placement level 1 in Figure 3. Therefore, more driving functions are placed at the lower placement levels. Functions become more dependent as the placement level increases. In this model, vector arrows represent the direct causal relationship among functions within successive placement levels. Consistent with the ISM standard procedure (e.g., Ching et al., 2022), the transitivity rule is ignored while constructing the interpretive structural model, meaning vector arrows visually present only direct relationships, and indirect relationships are ignored.

4.7 | MICMAC analysis

MICMAC analysis is a complementary approach to ISM that involves a graphical comparison of the system's components based on their driving power and dependence power (Ghobakhloo, Iranmanesh, et al., 2021). The matrix in Figure 4 represents the results of the MICMAC analysis. Under MICMAC analysis, the system's components (blockchain sustainability functions in the present study) should be classified into four quadrants. The autonomous quadrant includes functions with weak driving and dependence powers. TRD and CVO are the two autonomous sustainability functions of blockchain. Driver quadrant consists of functions with strong driving power but weak dependence power. STD, MAA, RSI, TAE, TPE, and CVM are categorized as driver sustainability functions of blockchain. The linkage quadrant consists of functions with strong driving and dependence powers. Functions in this quadrant are called linkage since they connect the enabling role of driver functions to the more dependent and complex functions. BPC is the only linkage sustainability function within the study. Finally, the dependent quadrant includes functions with weak driving power but strong dependence power. CPR, RCI,

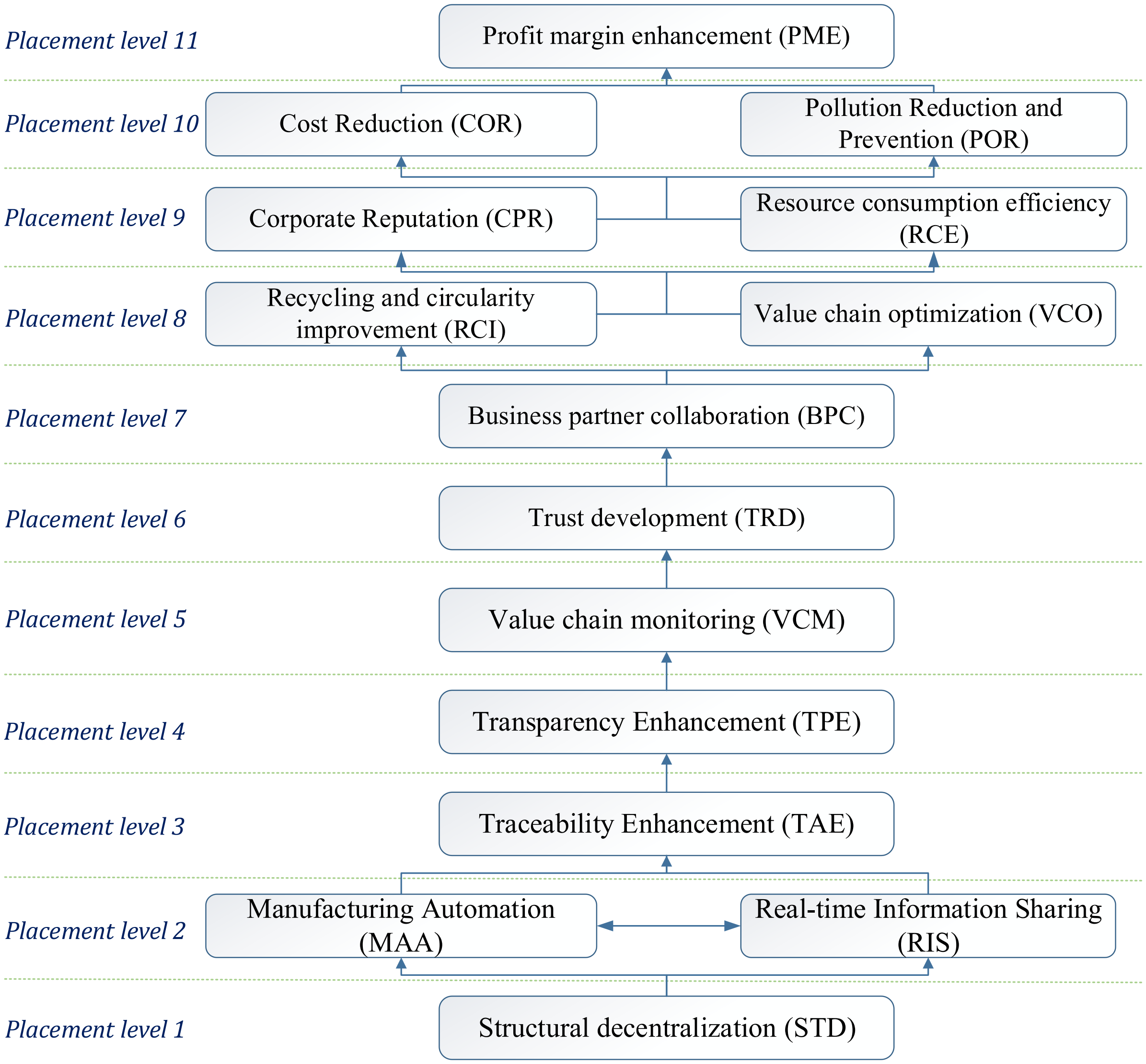


FIGURE 3 The interpretive structural model of blockchain-enabled sustainability.

POR, COR, RCE, and PME are the six dependent sustainability functions of blockchain. It means they are the least accessible and hard-to-develop blockchain functions, which significantly rely on the enabling role of linkage and driver sustainability functions.

5 | DISCUSSION

Experts believe emerging blockchain technologies might have important implications for sustainable development, and the interpretive structural model of blockchain-enabled sustainability presented in Figure 3 explains how blockchain can deliver valuable sustainability functions. Results indicate that blockchain contributes to sustainability by first creating distributed and decentralized decision systems across supply chains. This finding is supported further by the dominating role of the STD function observed within the MIMMAC matrix (Figure 4). Through P2P data networking, blockchain allows business partners to access value created more equitably. This fining supports Friedman and Ormiston (2022), who recently showed that the decentralization feature of blockchain acts as a basis of democracy in supply chains, promoting the concepts such as shared value or sustainable collaboration. The STD function further paves the way for the development of MAA and RCI. STD enables the MAA and RCI functions by creating the necessary data security, trust, and decentralized decision systems that sustain automation processes and streamline the adoption of 3D printers, Cobots, IIoT, and CPPS, advanced manufacturing technologies crucial to the smart factory concept.

MAA and RCI functions promote sustainability by breaking down information silos and improving resource planning, employee creativity, productivity analytics, process monitoring, and the working environment. Business partners can further draw on MAA and RCI functions to improve the traceability of supply chain operations. MAA

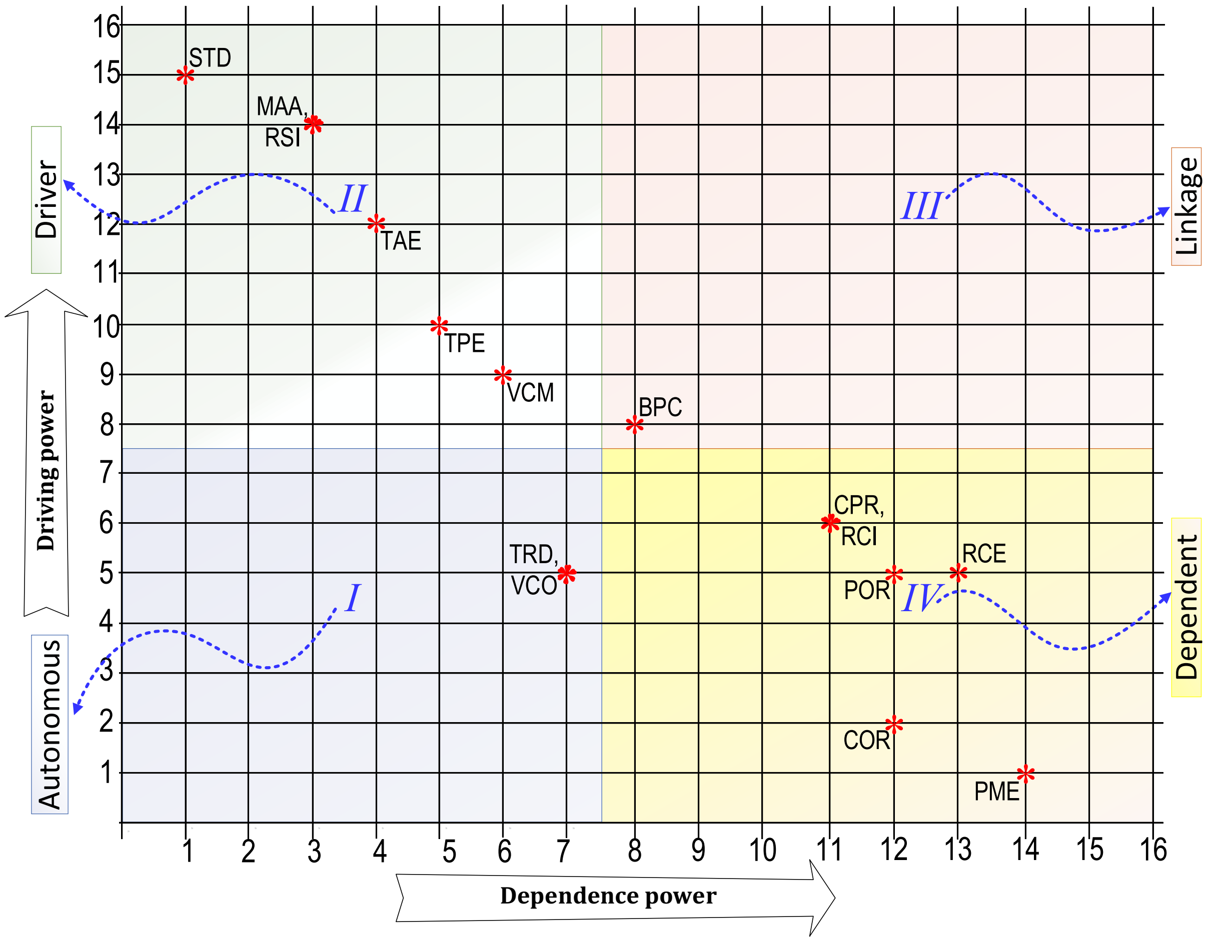


FIGURE 4 The MICMAC matrix.

enables the TAE function through the vertical integration of all smart components of the smart factory, from intelligent raw materials and components to smart machinery and equipment. The RCI function enables TAE by facilitating the horizontal integration of supply chain operations, facilitating supply chain mapping, and enhancing the data capture, recording, and management processes across the entire value chain. The TAE function of blockchain promotes sustainability by allowing supply partners to monitor the socio-environmental impacts of materials and products as they move through the value chain. TAE facilitates the early detection of supply chain bottlenecks and offers essential opportunities for minimizing the sustainability impacts of external or internal supply chain disruptions. More importantly, TAE is critical to developing the transparency enhancement (TPE) function. TAE creates a more transparent supply chain by increasing access to information on raw material origins, price records, certifications, and outsourcing compliance.

Blockchain TPE function incentivizes positive socio-environmental impact by increasing the accuracy of supply chain environmental sustainability assessments, sharing climate footprints of products, communicating customers' green purchase decisions, and clarifying business partners' contribution to the circular economy. Consistently, TPE acts as a critical enabler of the VCM function. Through the VCM function and by complementing IoT and cloud services, blockchain allows supply partners to better locate and track asset (e.g., raw material or final product) status and collect intelligence on supply chain bottlenecks or risks such as consumer-related disruptions or natural disasters. Through transparent and efficient monitoring of upstream suppliers, production, and distribution operations, blockchain further delivers the TRD function. TRD is critical to sustainability, given it allows supply partners to gain the shared empathy to develop deeper sustainable partnerships internally and integrate with external stakeholders responsibly. These features, complemented by the secure and dependable information-sharing features of blockchain, facilitate the Business Partner Collaboration (BPC) function. The BPC function is uniquely beneficial to sustainability given it is the only linkage function transferring the enabling role of *driver* functions such as STD, MAA, and RIS to more dependent and complex sustainability functions of blockchain.

BPC particularly draws on the smart contracting and data immutability features of blockchain to eliminate deviations from collaborative efforts on addressing prevailing sustainability issues such as energy transition or climate change. BPC further streamlines supply chain process integration and enables the RCI and VCO functions of blockchain. RCI and VCO are critical enablers of supply chain sustainability, given that they collectively allow supply chain partners to achieve optimal outcomes from their value chain activities. These functions serve sustainability by promoting recyclability and reducing value leaks, inefficiencies, bottlenecks, and waste across the value network. By introducing circularity and resource efficiency into supply operations, RCI and VCO enable the development of CPR and resource consumption efficiency (RCE) functions. The CPR and RCE functions of blockchain allow supply partners to commit more resources to develop various sustainability goals such as eliminating child labor, preventing waste, and integrating green materials or renewables. The CPR and RCE functions further pave the way to the materialization of COR, POR, and PME functions of blockchain.

COR, POR, and PME are the most remote and hard-to-develop sustainability functions of blockchain, given they cannot be genuinely developed unless blockchain has delivered the more driver sustainability functions. Nonetheless, COR, POR, and PME cannot be overlooked since they have invaluable implications for promoting sustainability. The POR function of blockchain empowers businesses to be proactive in their sustainability management strategies and reinvent their business models or implement smarter operations to prevent environmental pollution proactively. The COR and PME functions address the resource intensity concerns associated with implementing reactive and proactive sustainability management strategies. In general, most businesses struggle with affording various sustainability costs, such as aggressively priced green materials or the cost of integrating renewables, implementing smarter technologies, and adapting to human-centric practices. The COR and PME functions of blockchain address these issues by reducing the costs of operation and improving profitability, giving businesses the resource capabilities to implement sustainable thinking.

5.1 | Blockchain-driven sustainability roadmap

The main objective of the present study involved developing a strategy roadmap to elucidate the micro-mechanisms through which blockchain technology can be leveraged to facilitate sustainable development. We drew on ISM to identify the sequence in which the sustainability functions of blockchain should be leveraged to maximize the sustainability values of this technology synergistically. Although the ISM excels in interpreting the sequential relationships among elements of a system and identifying each element's driving and dependence power, it is limited in comparatively interpreting contextual relationships among the elements (Sushil, 2012). To describe how the sustainability functions of blockchain may interact and explain the functionality of each contextual relationship, the study followed the roadmapping methodology recommended by Ghobakhloo et al. (2022) and developed the strategy roadmap for blockchain-driven sustainability as Figure 5. In the present work, the purpose of strategy roadmapping is to outline the sustainability vision of blockchain and explain how this vision can be truly realized by mapping the sustainability functions of this technology and understanding the interactions and complementarities among the functions. This roadmap can offer the sustainability stakeholders, from companies and suppliers to customers and social actors, a synoptic yet detailed overview of how the 15 sustainability functions should be leveraged sequentially to realize the contribution of blockchain to sustainability synergistically.

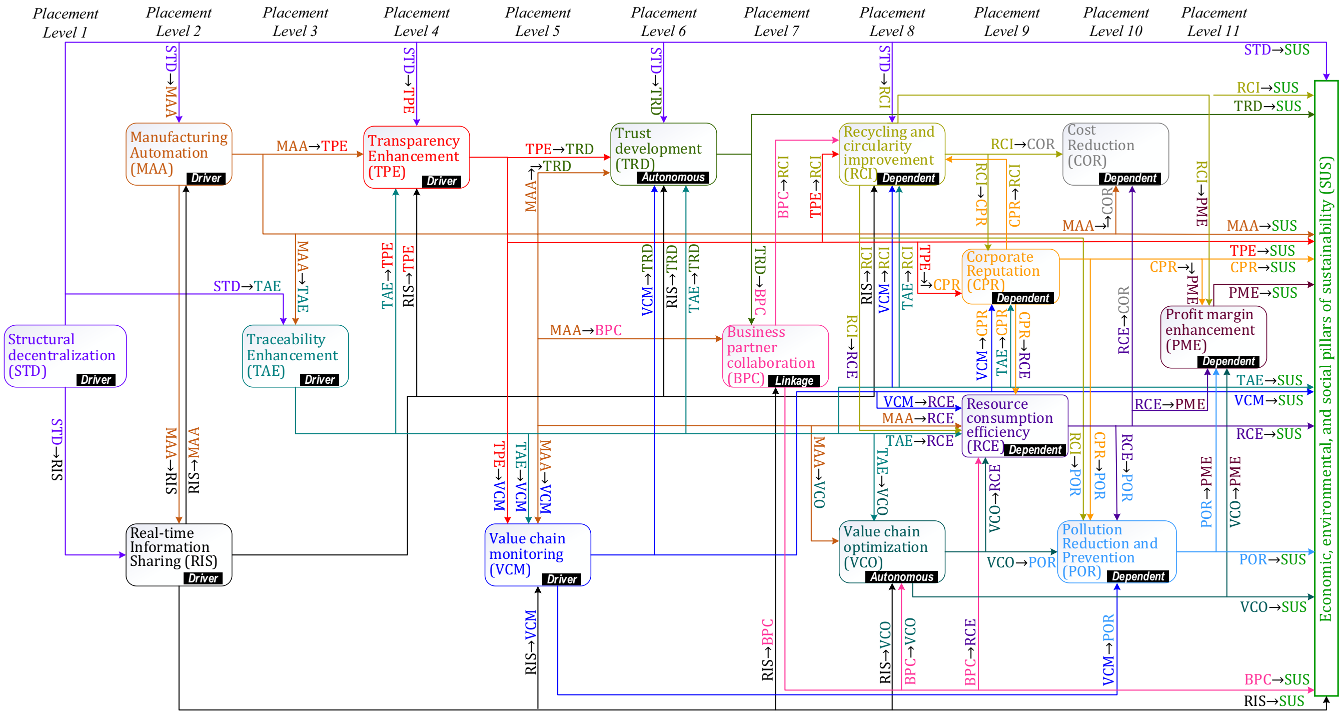


FIGURE 5 The interpretive strategy roadmap of blockchain-enabled sustainability.

The functions presented in this roadmap represent the 15 functions identified within the content-centric synthesis of the literature. Placement levels for functions and their contextual relationships in Figure 5 correspond to the ISM results, whereas their causality role corresponds to the results of MICMAC analysis. The most important objective of this roadmap is to answer the 'how' questions while interpreting the causal relationships. In other words, this roadmap strives to explain *how* a given function can impact or be impacted by other functions and *how* it can contribute to various aspects of sustainable development. Due to the complexity of this roadmap, the interactions visualized in Figure 5 are described in Table A1, Appendix A. For example, referring to Figure 5 and Table A1, Appendix A, the MAA → BPC relationship implies that the automation (MAA) function of blockchain would enable the business collaboration (BPC) function via enhancing the status awareness and engagement of collaborators concerning shared projects, simplifying interactions among employees across various functional departments, and eliminating repetitive tasks from collaboration responsibilities.

The roadmap further outlines that each sustainability function of the blockchain can only boost certain aspects of sustainable development. For example, RIS excels at streamlining sustainability performance management and improving product life cycle management. Alternatively, VCM mainly promotes the economic part of sustainability, for example, via optimizing intralogistics and lowering overhead costs. This finding implies that all sustainability functions of blockchain are essential since they complement each other in boosting sustainable development.

6 | CONCLUSION

The application of blockchain technology in the business environment is in its embryonic stage. However, scholars believe that blockchain can offer invaluable opportunities for promoting economic, environmental, and social pillars of sustainability. Despite recent advancements in understanding the sustainability implications of blockchain, the mechanism through which distributed ledger technology delivers sustainability values is largely unknown. The present study attempted to address this knowledge gap by developing an interpretive strategy roadmap of blockchain-enabled sustainability that details such an underlying mechanism. The study conducted a content-centric literature review and identified 15 functions through which blockchain contributes to sustainability. The study further applied the ISM technique to understand how these sustainability functions interact while delivering the sustainability value of blockchain technology within the business environment. The findings are believed to offer notable implications for research and practice.

6.1 | Contributions to theory and practice

The study contributes to theory by providing a comprehensive framework for understanding the intricate mechanisms through which blockchain technology can enhance sustainable development. The research elucidates how blockchain can foster sustainability by creating distributed and decentralized decision systems across supply chains, thus promoting equitable access to shared value. This aligns with the idea that the decentralization feature of blockchain acts as a basis for democratic principles in supply chains. Through functions such as MAA and RCI, blockchain further advances sustainability by enhancing traceability, resource planning, and overall supply chain operations.

The study underscores the critical role of transparency enhancement, which allows for monitoring socio-environmental impacts and early detection of bottlenecks in supply chains. Such transparency is essential for sustainable collaboration and shared value creation. Business partner collaboration leverages smart contracting and data immutability features of blockchain to eliminate deviations from collaborative efforts, particularly in addressing sustainability challenges. This collaboration streamlines supply chain processes, enabling RCI and VCO.

Notably, the study outlines the functions of blockchain that are essential for sustainability, including CPR, resource consumption efficiency, COR, POR, and PME. These functions address resource intensity concerns and offer businesses the capabilities to implement sustainable practices effectively. The study's insights are valuable for understanding how various sustainability functions of blockchain can interact and contribute to sustainable development. The developed roadmap provides a synoptic yet detailed overview of how these functions should be sequentially leveraged to maximize their synergistic impact on sustainability. This roadmap serves as a valuable resource for sustainability stakeholders, offering a clear understanding of the causal relationships among the functions and how they can be utilized to promote various aspects of sustainable development. It highlights the interdependence of these functions, emphasizing their complementarity in advancing sustainability.

The study also offers notable implications for practice. Findings revealed that blockchain allows industrial supply chains to significantly boost economic, environmental, and even social sustainability performance. Nonetheless, blockchain delivers these values through an incredibly complex mechanism, and contemporary supply chains must have the ability to identify this mechanism and strategically capitalize on its underlying sustainability functions. Blockchain delivers sustainability values through a specific sequential order. Indeed, the precedence relationships identified within the 15 sustainability functions of blockchain signal such a complex order. Accordingly, industrial value chains should capitalize on blockchain's unique features to first achieve STD and modularity by distributing decision-making controls to the supply chain micro-nodes. This blockchain function would allow supply chains to promote the automation of manufacturing nodes under the smart factory concept and further achieve RIS vertically and horizontally. Under such circumstances, blockchain can effectively deliver the supply chain traceability and transparency functions, which in turn streamline value chain monitoring. These driver functions of the blockchain (STD, MAA, RIS, TAE, TPE, and VCM) may not directly relate to sustainability performance. Nevertheless, they are indispensable to sustainability, given that they enable critical functions that can directly translate to the improved sustainability performance of supply chains.

Indeed, the driver functions of blockchain promote trust-based responsible supplier collaboration and customer relationship management. By doing so, blockchain allows business partners to collaborate on optimizing supply chain operations closely and incorporate circularity in the supply chain strategies. Through these functions, supply partners can better utilize blockchain features to achieve resource consumption efficiency and pollution prevention across various operations and better communicate their sustainability reputation through blockchain-enabled openness and transparency.

Findings also explain that blockchain can provide supply partners with substantial COR and profitability opportunities. Nonetheless, these are the least accessible benefits of blockchain. Businesses should have the necessary competencies to use blockchain features to capitalize on enabling functions that are prerequisites for blockchain-enabled COR and profitability. Interestingly, this finding shows that blockchain plays a unique role in promoting economic and socio-environmental aspects of sustainability across industrial supply chains. Ching et al. (2022) recently studied the contribution of Industry 4.0 technologies (e.g., additive manufacturing, IIoT, autonomous robots) to sustainable manufacturing and revealed that these technologies first deliver the manufacturing-economic aspect of sustainability through reducing manufacturing costs and improving profit margin. Interestingly, Ching et al. (2022) showed that socio-environmental outcomes such as emission reduction or employment opportunity development are the least accessible and hard-to-develop contributions of these technologies. Thus, Industry 4.0 is mainly known as a productivity/profit-driven phenomenon. In contrast, the present research revealed that blockchain primarily prioritizes addressing socio-environmental concerns such as equitable distribution of wealth, circularity, renewables, and pollution prevention. This observation does not necessarily denote blockchain's inability to promote economic productivity and profitability. Instead, it shows that blockchain takes a more counter-intuitive and equitable approach to generate value, mainly through reframing the value-creating landscape and addressing the long-lasting sustainability problems such as unequal wealth distribution, inefficiencies, and waste.

The present study and the current understanding of blockchain-sustainability interactions can be extended by future research in several ways. The present study held an optimistic perspective while mapping the contributions of blockchain to sustainability. Nonetheless, integrating blockchain into business operations is knowledge and resource-intensive. Since most typical supply chains and smaller businesses may not have the necessary resources to invest in blockchain, industry leaders might capitalize on blockchain to reinvent their business models and monopolize the means of value-creating. More importantly, using blockchain in the supply chain management context is challenged by numerous issues, such as interoperability concerns, lack of industry-wide standardization, or legal hurdles. Future studies are invited to address these concerns and identify strategies that allow businesses to position themselves strategically to capitalize on blockchain efficiently and equitably.

Blockchain closely interacts with other technological constituents of Industry 4.0, such as IoT, cloud computing, and AI, to deliver the sustainability functions identified. For example, experts believe blockchain can resolve the explainable AI challenge by increasing trust in data integrity and security. Alternatively, AI models can be integrated into blockchain-based smart contracts to expedite and optimize logistics operations such as reordering or payment execution. While acknowledging the mutual dependability of blockchain and other modern digital technologies, the present study could not conceivably explain these possible interactions while identifying blockchain sustainability functions. Thus, future studies are invited to explore how blockchain can integrate with modern disruptive technological innovations to offer new and more efficient ways of promoting sustainable development.

6.2 | Limitations and future directions

The strategic roadmap presented in this study offers a compelling picture of a holistic but idealistic scenario where blockchain technology, when governed effectively at the firm and supply chain levels, becomes a formidable driver for promoting a multitude of sustainability values. It envisions a world where blockchain serves as a catalyst for improving corporate productivity and profitability without compromising essential environmental and social values. While this vision is undoubtedly captivating, it is essential to acknowledge the multifaceted challenges and limitations that exist, constraining the seamless integration of blockchain into business operations aligned with sustainability.

In the scenario depicted in this study, blockchain operates as a transformative force with the potential to enhance various aspects of corporate and supply chain sustainability. For example, blockchain's immutable ledger can ensure transparency, allowing stakeholders to trace the provenance of products, and ensuring ethical sourcing and production. Through smart contracts and automated processes, blockchain can streamline operations, reducing waste and inefficiencies. Blockchain can further foster trust by enabling consumers to trace product journeys and make informed ethical choices.

However, the real-world implementation of blockchain for sustainability faces significant challenges. Notably, blockchain must seamlessly integrate with existing systems, which can be complex in organizations using diverse technologies. This challenge is magnified when extending integration to external partners and suppliers with their own systems. Blockchain's transparency and immutability features may challenge data privacy and security, especially when storing sensitive information. Under such circumstances, the evolving regulatory landscape presents a significant hurdle. Differing regulations across jurisdictions add layers of complexity, making compliance difficult. Alternatively, energy-intensive consensus mechanisms in some blockchain networks pose environmental concerns, as high energy consumption conflicts with sustainability goals. In the same vein, the efficiency gains achieved by blockchain may lead to increased energy consumption due to additional transactions, potentially offsetting sustainability benefits. More importantly, the scarcity of blockchain expertise within organizations presents a multifaceted challenge, primarily rooted in the complexity of blockchain technology, the lack of in-house talent, soaring demand for blockchain professionals, the rapid evolution of the field, integration complexities, security and risk management considerations, and the strategic nature of blockchain decisions. The implications of this shortage range from suboptimal implementations and security vulnerabilities to strategic misalignment.

While academic literature has recognized the obstacles and limitations hindering the smooth integration of blockchain technology into corporate and supply chain sustainability, a significant gap exists in our practical understanding of how various blockchain stakeholders, such as businesses, consumers, technology developers, and government entities, can pragmatically overcome these challenges. Although scholars have thoroughly discussed the difficulties and complexities, there has been insufficient focus on real-world solutions. This gap highlights the crucial need for practical and effective approaches to unlock blockchain's untapped potential in promoting sustainability within business and supply chain operations. Future research should prioritize addressing these significant knowledge gaps and tackling the intricate challenges impeding the smooth integration of blockchain technology in corporate and supply chain operations. These endeavors should encompass empirical investigations and comprehensive case studies aimed at extracting practical solutions from successful real-world implementations. Encouraging cross-sector collaboration among academia, industry, government, and non-governmental organizations is essential to leverage multidisciplinary expertise. It is imperative to delve into the evolving regulatory landscape and its implications for sustainability objectives. Furthermore, research on skill development, training, eco-friendly blockchain practices, inclusive governance models, knowledge-sharing platforms, and longitudinal studies can offer actionable insights. Embracing these research directions will enable a collective effort to confront these challenges and pave the way for a more sustainable and inclusive future within the realm of blockchain technology.

On the final note and concerning the possible limitation of the study, the small size of the expert group in our study presents a potential limitation that future research endeavors could address by purposefully including experts from various backgrounds and fields of expertise. Such an approach has the potential to enhance the generalizability and dependability of insights into the topic.

AUTHOR CONTRIBUTIONS

Morteza Ghobakhloo: Conceptualization, Funding Acquisition, Investigation, Methodology, Project Administration, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing. **Mohammad Iranmanesh:** Conceptualization, Formal Analysis, Project Administration, Supervision, Writing – Original Draft Preparation, Writing – Review & Editing. **Muhammad Shujaat Mubarik:** Conceptualization, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing. **Muhammad Faraz Mubarak:** Conceptualization, Investigation, Administration, Supervision, Visualization, Writing – Original Draft Preparation. **Azlan Amran:** Investigation, Project Administration, Supervision, Validation, Writing – Original Draft Preparation. **Ahmad A. A. Khanfar:** Methodology, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing.

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APPENDIX A

TABLE A1 Interpretive logic-knowledge base matrix for sustainability functions of blockchain.

Contextual relationship	Enabling role
Structural decentralization (STD)	
STD → MAA	Better process/task identification and independence for automation; improved monitoring and measurement of autonomous tasks
STD → RIS	Reduced complexity of seamless communication; improved interoperability of information and operations technologies
STD → RCI	Improved decision process concerning circularity functions such as recycling, reusing, and refurbishing across the manufacturing supply chain
STD → TAE	Efficiency of enabling technologies such as automated identification, data capturing, and data processing tools; systemization of record keeping and exchange
STD → TPE	Simplified implication of transparency levers across the supply chain for closing information gaps; reduction of supply chain functional complexity
STD → TRD	Geographic responsiveness to regional stakeholders; faster responsiveness to events due to decentralized insights into customers and suppliers
STD → SUD	Improved manufacturing and supply chain resilience; workplace safety and reduced risks and accidents; improved customer experience
Manufacturing Automation (MAA)	
MAA → BPC	Meaningful and simplified interactions among employees of various functional departments; improved status awareness and engagement of collaborators concerning shared projects; removal of repetitive tasks from collaboration responsibilities
MAA → COR	Reduced cost of quality; reduced maintenance costs; higher production output; higher manufacturing productivity
MAA → RIS	Seamless communication capability via enhancing the integrability of modern and legacy information and operations technologies; autonomous data access request management
MAA → RCE	Automation and optimization of inventory management systems; reduction of manufacturing waste outputs; streamlining the integration of recycled materials into the production operations; designing of modular and more resource-efficient products
MAA → TAE	Autonomously updating the contract status, production status, and material sourcing status; efficiency of traceability systems; elimination of human errors in traceability systems; autonomous tracking of production processes, from raw material acquisition to packaging and customer delivery
MAA → TPE	Autonomous collection of granular, security-rich, and verifiable production data across the manufacturing chain; making workflow paperless and highly visible; early error, risk, or fraud detection
MAA → TRD	Streamlined implementation of identity verification system within the production facilities
MAA → VCM	Improved mapping and monitoring via supply-chain-wide standardization of processes, strategies, and functions; reduction of supply chain complexity; reduction of human errors via automating manual processes
MAA → VCO	Reduction of manufacturing and product development costs; improved order fulfillment; optimal production management decision-making; lower cost of maintenance
MAA → SUS	More efficient resource consumption; integration of renewable resources; waste prevention; more efficient recycling and repurposing; improved product quality; improved transportation and intralogistics
Real-time Information Sharing (RIS)	
RIS → BPC	Removal of information and functional silos; improved collaborative effectiveness and experience within and across businesses; improved collaborator engagement; efficiency of collective decision processes
RIS → MAA	Seamless monitoring of automated processes, machinery, and requirements; better process integration; improved accessibility information from software robots
RIS → RCI	Improved accessibility of critical information on circularity loops; streamlined management of asset performance and health
RIS → TPE	Effectiveness of intra and inter-organizational communications; improved accessibility of relevant information within and across functional units
RIS → TRD	Efficiency of integrated collaboration management tools; streamlined sharing of proprietary data; Boosting cyber-security of collaboration platforms
RIS → VCM	Streamlined identification of risks and opportunities across various production stages; more inclusive integration of supply nodes into the monitoring tools
RIS → VCO	Improved supply chain forecasting accuracy; higher agility of supply chain decisions; more productive human resources and talent management
RIS → SUS	Streamlined sustainability performance management; employee empowerment; improved product life cycle management

TABLE A1 (Continued)

Contextual relationship	Enabling role
Traceability Enhancement (TAE)	
TAE → CPR	Product certification visibility and improved customer experience; More visibility into the socio-environmental values of processes, products, and services
TAE → RCI	Improved governance of circular trade flow regulations; improved supply chain mapping; compliance with the socio-environmental due diligence checks
TAE → RCE	Efficiency of resource and waste management decision tools such as value stream mapping; enabling renewable material sourcing
TAE → TPE	Improved disclosure of supplier information; better insights into business vulnerabilities and risk points
TAE → TRD	Dynamic risk mitigation strategies via data-driven risk assessment and evaluation approaches; boosting customer trust via minimizing the risk of tempering or intervention
TAE → VCM	Improved tracking of materials, labor, final products, and resources across the value network; improved risk and weak point recognition capability within various supplier tiers
TAE → VCO	More responsive customer service; reduced customer service costs; improved customer-supplier relationship; efficiency of outsourcing activities
TAE → SUS	Emission source identification and tracking; product safety tracking and assurance; COR via preventing deadlock occurrence
Transparency Enhancement (TPE)	
TPE → CPR	Contribution to building a stronger brand identity; improved product reliability and dependability; higher customer loyalty
TPE → RCI	Accessibility of high-level supply chain information concerning, for example, certifications or product components; Streamlined processing of end-of-use consumer goods
TPE → TRD	Improved visibility into the credibility of sustainable sourcing; improved accountability of value partners toward all stakeholders
TPE → VCM	Mapping the entire supply network to have visibility into the entire supply base within various tiers; efficiency of analytic tools in measuring and monitoring all influential supply performance metrics
TPE → SUS	Improved socio-environmental accountability of organizations; more efficient sustainable practices; visibility into the environmental impacts of products; employee empowerment
Value chain monitoring (VCM)	
VCM → CPR	Offering quality products and services; improving customer experience; improving the prospect of growth and innovation
VCM → POR	Efficiency of waste audits across the supply chain; improved execution of waste management action plan; improved monitoring of waste streams
VCM → RCI	Better monitoring and anticipation of disruption within the circular operations; improved scalability of circularity solutions across the supply chain
VCM → RCE	Improving the internal and supply-chain-wide reuse and recycling of wastes (e.g., faulty products; repair items, materials, etc.); better identification of potentials for resource consumption reduction points across the supply chain
VCM → TRD	Reliability and dependability of performance metrics and insights; more productive post-performance audits
VCM → SUS	Resource efficiency via inter and intralogistics optimization; agility-driven supply chain resilience; improved risk management; lower overhead costs; reduction of corporate footprint
Trust development (TRD)	
TRD → BPC	Improved sense of safety and ownership in the collaboration environment; higher propensity to take appropriate risks in collaboration; boosting knowledge sharing and open communication
TRD → SUS	Integration and partnership for sustainability; adoption of sustainable processes and products; improved working environment; stakeholder (e.g., customer or employee) satisfaction
Business partner collaboration (BPC)	
BPC → RCI	Collective development of cross-sector circular solutions; boosting circularity solutions via R&D partnership; Enhancing the commercial viability of circular solutions; joint circularity learning; circularity financial alignment
BPC → RCE	Resource efficiency via collaborative business mode, product, and process innovation; collective development and enforcement of resource conservation policies within supply chains
BPC → VCO	Accessibility of historical and current supply chain data; faster and more accurate decisions across operations life cycle
BPC → SUS	Collective development of green absorptive capacity; supply chain-wide empowerment of sustainable innovation orientation; boosting shared value concept; green product and process innovation

(Continues)

TABLE A1 (Continued)

Contextual relationship	Enabling role
Recycling and circularity improvement (RCI)	
RCI → CPR	Upholding and delivering environmental sustainability values; becoming a benchmark brand for boosting sustainable development
RCI → COR	Development and an environmentally aware brand; better integration of sustainability value into the corporate goals and strategies
RCI → POR	Hierarchization of waste for various circularity purposes (e.g., reusing or recycling); the systematic shift from desponding to recusing across the industrial operations; development and implementation of waste reduction agenda
RCI → PME	Reducing resource intensity; lowering energy costs; reducing compliance costs; higher demand for greener products
RCI → RCE	Optimization of the product life cycle; recycling of various manufacturing wastes, from defects to lubricants and fluids used in production operations; reusing of waste material and refurbishing of defective products
RCI → SUS	Reduced emissions; resource productivity; prevention of environmental degradation; economic growth and profitability; job creation; improved corporate image
Value chain optimization (VCO)	
VCO → COR	Reduction of reputational risks across the supply chain; the ability to deliver promises; resilience and adaptability to disorders
VCO → PME	Reduction of overhead costs; optimization of supply chain costs; higher revenue due to improved order fulfillment
VCO → RCE	Optimization of inter/intra logistic transportation routes; higher resource productivity via improved supply chain planning and execution
VCO → SUS	Supply chain resilience; sustainable procurement and integration of green materials; improved corporate social responsibility across the supply network
Corporate Reputation (CPR)	
CPR → POR	Becoming an industry leader in addressing prevailing sustainability concerns such as climate change, environmental degradation, or rebound effect; reputation in resiliency against supply disruptions and business turbulence
CPR → PME	
CPR → RCI	Attraction of circularity talents; inadvertent commitment to the circular economy; higher capital for circular solution investments
CPR → RCE	Commitment to strategies for promoting resource efficiency, such as renewable resourcing, inventory management optimization, and formal waste management programs
CPR → SUS	Higher resource availability for promoting sustainability goals; Inadvertent commitment to minimizing environmental footprint
Resource consumption efficiency (RCE)	
RCE → COR	Promoting a spotless brand via ethical sourcing; more immutability to supply chain disruptions
RCE → POR	Reduction of raw material, energy, and chemical inputs across production processes
RCE → PME	Reduction of organizational risk points; reduction of waste management costs
RCE → SUS	Natural reserve preservation; emission reduction; industrial waste reduction; manufacturing resilience
Pollution Reduction and Prevention (POR)	
POR → PME	Reduction of pollution management costs; reduction of employee safety and health costs; reduction of costs associated with regulatory requirements
POR → SUS	Improved safety and health of employees; improved stakeholder relations; environmental preservation
Profit margin enhancement (PME)	
PME → SUS	Investment in cleaner production technologies; employment of sustainability talents; renewable integration; sustainable smart product development